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ARCTIC ICE AND SEA TEMPERATURE ANOMALIES IN THE NORTHEASTERN NORTH ATLANTIC AND THEIR SIGNIFICANCE FOR SEASONAL FORESHADOWING LOCALLY AND TO THE EASTWARD [1]

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ABSTRACT

An analysis was made of a combined 6 yr with an extreme northerly ice limit and relatively high sea temperatures and 6 yr with an extreme southerly ice limit and relatively low sea temperatures, respectively, in the northeastern North Atlantic during April–September and the contemporary and subsequent October–March air temperatures and precipitation locally and to the eastward.

The results obtained indicate a relationship with the contemporary and, because of the persistence of the circulation, also the subsequent cold season temperature and precipitation progressively later in Iceland, Europe, the Middle East, northern Pakistan, and India, in keeping with the general movement of weather systems from west to east in the middle and high latitudes.

One may expect, following further study of the relationship from a consideration of anomalies of individual years, that a basis for foreshadowing the cold season temperature and precipitation in the northeastern North Atlantic, Europe, the Middle East, northern Pakistan, and India will become available early in October.

1. INTRODUCTION

The areal extent of the ice at the time of its maximum extent in the Arctic Ocean is 10.8×10^6 km^2 and in the Southern (Antarctic) Ocean 18.8×10^6 km^2. The significance of the two large icepacks for the general climate and weather has long been known. Less known is the significance of their variations (ice limit) from year to year and from one longer period to another as an index of the cold polar water outflow and (because of the persistence characteristics of large-scale oceanic and atmospheric processes) of effects on the subsequent weather over the oceans and to the eastward in the higher and middle latitudes.

Here, we shall consider the variations in the ice limit in the northeastern North Atlantic (Greenland Sea) and in the penetrations of the cold water beyond the ice limit for their possible effect on the storminess, temperature, and precipitation in eastern Greenland, Iceland, Europe, the Middle East, northern Pakistan, and India, which are traversed by North Atlantic storms and the secondaries developing on the way as, for example, in the Mediterranean.

Since the equatorward penetration of ice and of cold water from higher latitudes are themselves to a great extent determined by the winds, both during and before the ice season, we would want to consider also relationships with the subsequent ocean and weather anomalies. We must remember that, while the relations of the winds with subsequent ice conditions can be delineated more closely (Schell 1962, 1964; Strübing 1967), the use of the winds for correlations with ocean and weather anomalies *still farther in time* could obscure and diminish these relationships.

The possibility that variations in the ice limit in the oceans can serve as a significant index of the large-scale contemporary oceanic and atmospheric anomalies (and because of the persistent character of the hydrological process and also of subsequent weather) was explored by Wiese (1924) following the pioneering efforts of Brennecke (1904), Meinardus (1906), and others. Wiese showed that a more southerly boundary of the ice in the northern North Atlantic during April–August, presumably associated with a displaced zone of convergence of the cold polar and warm North Atlantic waters, was also associated with a more southerly position of the North Atlantic storm track; and this was later shown by Schell (1947), with heavier precipitation in the fall and early winter over Ireland, the United Kingdom, southern Norway, Sweden, Denmark, Holland, and France but with lighter precipitation over northern Norway, as the Arctic High extends southward and the storms are forced to a lower latitude (see also Brooks and Quennell 1928, Walker 1947, and Lamb and Johnson 1959). Walker's study was statistical and without any substantial meteorological guideposts, leading him to think of the individual correlation coefficients as one of the hundreds obtained by chance. When his results for the northern North Atlantic and northwestern Europe are arranged in accordance with the physical synoptic considerations outlined above, they confirm rather than vitiate, as he thought, the variously indicated relationships between the ice limit in the Greenland Sea and the weather in the northern Atlantic and western Europe.

For example, the positive sign of his correlation coefficients with Stykkisholm (Iceland) pressure and nega-

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TABLE 1.—*Autocorrelation coefficients (sea-surface temperature) for single months, adapted from Schütte (1967)*

Time lag (no. of months)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Puerto Chicama (1925–1965)												
1	0.60	0.65	0.73	0.89	0.86	0.90	0.93	0.93	0.95	0.93	0.86	0.79
2	.44	.53	.60	.73	.73	.86	.82	.89	.87	.85	.62	.41
3	.23	.51	.62	.66	.74	.76	.77	.77	.80	.64	.31	.55
4	.12	.57	.57	.73	.67	.75	.64	.78	.60	.38	.37	.26
6	.14	.47	.62	.70	.62	.66	.43	.29	.31	.17	.00	.03
Average	.51	.55	.63	*.74*	*.72*	*.79*	*.72*	*.73*	*.71*	.59	.43	.41
Canton Island (1950–1965)												
1	0.95	0.92	0.90	0.85	0.92	0.95	0.97	0.96	0.98	0.97	0.96	0.95
2	.85	.78	.66	.90	.86	.89	.94	.93	.93	.95	.92	.94
3	.69	.51	.70	.70	.78	.85	.90	.88	.94	.92	.89	.83
4	.39	.55	.42	.65	.75	.77	.84	.90	.90	.93	.82	.61
6	.09	.24	.28	.46	.66	.78	.79	.85	.83	.61	.31	.34
Average	.59	.60	.59	.71	.79	*.85*	*.89*	*.90*	*.92*	*.88*	.78	.73

tive sign with the pressure at Thorshavn (Faeroes), to the southeast, are in agreement with an intensification of the Greenland High and a southeastward displacement of the low-pressure belt in the northeastern North Atlantic with a more southerly limit of ice in the Greenland Sea. Similarly in agreement are the negative sign coefficients obtained by him with the temperature at Spitzbergen, Gjesvaer (northern Norway), and Thorshavn. The smallness of the coefficients obtained by him were due in part to a somewhat loose selction of the time intervals in his correlations.

2. PERSISTENCE IN THE OCEANS

The phenomenon of persistence in the oceans or the tendency for averaged conditions over a certain period, such as a month or season, to persist for some time afterward is due in part to the inertia of water masses as a result of their greater density and in part to their greater heat capacity as compared to air. It has long attracted the attention of macrometeorologists. However, because only few areas of the world's oceans have been observed over a long period of time, the study of this phenomenon has proceeded very slowly and was in general limited to coastal or island stations and only recently to observations from fixed stations (Ocean Weather Ships, OWS) and those by merchant and other vessels in the open ocean (see below).

In a recent study, for example, of the sea-surface temperature at Puerto Chicama off the coast of South America (1925–1965) and at Canton Island in the equatorial Pacific (1950–1966), strong persistence was found at both stations (Schütte 1967). The greater average persistence at Puerto Chicama in the cold months ($r \geq 0.7$) than in the warm months (Southern Hemisphere) reflects the Peru Current, which is more dominant in winter (April–September) than in summer (October–March). Similarly, the more marked average persistence at Canton Island from June to October ($r \geq 0.8$) reflects the influence of the Peru Current's reaching Canton Island (downstream) some 2 mo later (table 1).

A similar analysis of the persistence in the sea-surface temperature at Papey (4 mi from the east coast of Iceland, where it is washed by the East Iceland Polar Current and an admixture of warm Atlantic water coming from the west and rounding Iceland along the north coast) gave, for the correlations of January–March with the following April–September period, $r=0.67$ (1874–1965); the April–September with the following October–December, $r=0.56$ (1874–1965); and of the October–December with the following January–March quarter temperatures, $r=0.69$ (1875–1965).

Also Nazarov (1968), from an analysis of the mean monthly sea-surface temperatures based mainly on observations obtained at the eight OWS stations in the North Atlantic (1948–1959), has found that their anomalies most often persist from between 7 to 12 mo. The duration of the anomaly (regardless of its magnitude) is related to the size of the area—the longer the duration, the larger the area similarly affected (see also Faegri 1950 and Kraus 1955). Persistence was recently found also by Namias (1970) for the North Pacific, using averaged latitude circle sea-surface temperatures.

As the East Iceland Polar Current (fig. 1) would be expected to influence the temperatures to the southeast, we find a small yet significant correlation ($r=0.39$, $n=89$) of the April–September sea-surface temperature at Papey off the east coast of Iceland with the following October–December temperature at Thorshavn in the Faeroes, which the current approaches with varying nearness from the northwest (Knudsen 1905 and Hermann 1948).

As another index of the influence of the cold water outflow from the Arctic at Thorshavn, we may consider the ice limit of the Greenland Sea-Barents Sea. Thus, the correlations of the conveniently available 49-yr series of the Greenland Sea-Barents Sea April – August ice limit with the following September–November and December–February sea-surface temperature at Thorshavn are

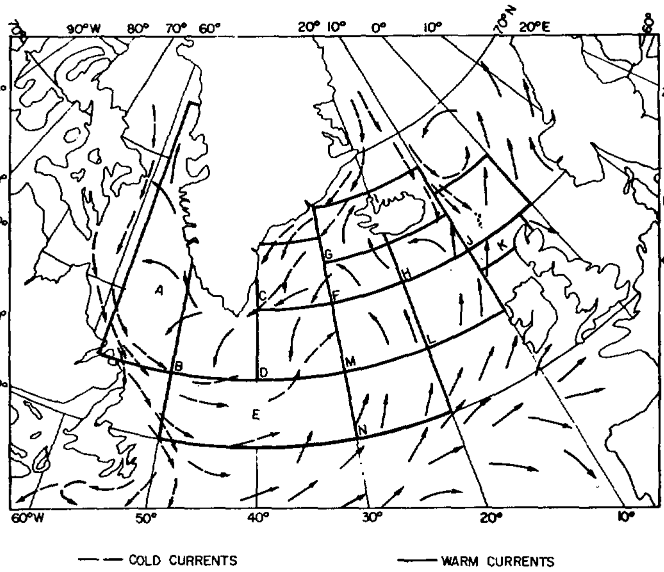


FIGURE 1.—Cold currents and warm currents.

greater than the correlations of the April–August Papey temperatures with the following Thorshavn temperatures (table 2).

This suggests that the Greenland Sea-Barents Sea ice severity is a better index of the outflow of cold water from the Arctic and its influence to the southeast (Faeroes) than the sea-surface temperature at Papey. The temperatures at Papey reflect also the inflow of Atlantic water rounding Iceland's north coast from south and west (Irminger Current) (Stefánsson and Gudmundsson 1969).

3. DATA

ICE

The ice data used in this study were taken from *Isforholdene i de Arktiske Have* (Ice Conditions in the Arctic Seas) and *Isforholdene i de Grønlandske Farvandte* (Ice Conditions in the Greenland Waters), both from the Danske Meteorologiske Institut (1877–1956 and 1957–1963); compilations of the ice limit for the waters north of Iceland by Eythorsson (1964); *Annales Biologiques*, Conseil permanent International l'Exploration de la Mer; and monthly ice charts, "Ice at the End of the Month," in *The Marine Observer* of the Meteorological Office, Marine Division, Bracknell, England (1931–1965).

In the past, information on the southerly extent of the ice or ice limit was from observations of seal-hunting ships operating along the edge of the icepack, fishery trawlers venturing into the more northerly water, expedition vessels, and also from observations at points along the coast, notably in Iceland since its settlement days. The observations from shipboard tended to make the ice conditions appear more severe than they actually were since, when a ship is near the ice limit, the possibility of determining whether the ice edge was the actual limit

TABLE 2.—*Correlations of April–August Greenland Sea-Barents Sea ice and Papey sea-surface temperatures with the following September–May sea-surface temperatures at Thorshavn (n=49, 1895–1939 and 1946–1949), from Schell (1956a)*

Thorshavn temperature	Greenland Sea-Barents Sea ice	Papey sea-surface temperature
	(r)	(r)
Sept.-Nov.	−0.50	0.35
Dec.-Feb.	−.46	.35
Mar.-May (following year)	−.26	.39

of the pack or just a detached ice belt did not always exist.

Despite this and other limitations, the early information of ice conditions in the Arctic Ocean served to outline the broad character of the ice conditions over a longer time interval, such as a season, due in part to the conservative nature of the icepack.

Beginning approximately with World War II, information on ice conditions in the northern North Atlantic became increasingly available from air reconnaissance. This made it possible to obtain information in more detail and also for all months of the year instead of only during spring and summer. In recent years, a new phase of ice observations developed with orbiting satellites.

A more southerly limit of the ice in the Greenland Sea, associated as a rule with northerly winds, may be identified by a close approach of the ice limit to the north coast of Iceland; this ice limit extends in an easterly direction beyond Iceland. As an example, we may cite April 1965 when ice (fig. 2) from the Greenland Sea lay close to this coast several months of the year and extended eastward. Similarly, as an example of a less southerly limit of the ice, we may show April 1960 when the ice (fig. 3) lay relatively far off the coast of Iceland much of the year and the ice limit turned sharply northward.

A close approach of the ice to the North Cape, the portion of Iceland that protrudes northwestward, is by itself no indication of severe ice conditions. The presence of ice off the North Cape could be the result of a southwesterly gale driving the ice off the lower east Greenland coast northeastward (British Admiralty Hydrographic Office 1946). This condition is, however, the exception.

Thus on the basis of the available information during the 1944–1965 period examined, we can identify the years 1965, 1963, 1959, 1952, 1949, and probably also the World War II year 1944 as severe ice years and the years 1960, 1957, 1956, 1954, and 1947 as light ice years.

SEA-SURFACE TEMPERATURES

Hydrographic surveys off the coasts of Iceland, made sporadically at first, have increased in frequency since World War II and especially beginning with the late 1950s when sections extending into the Greenland and Norwegian Seas yielding sea-surface and subsurface temperatures and salinities were made regularly (Stefánsson 1949,

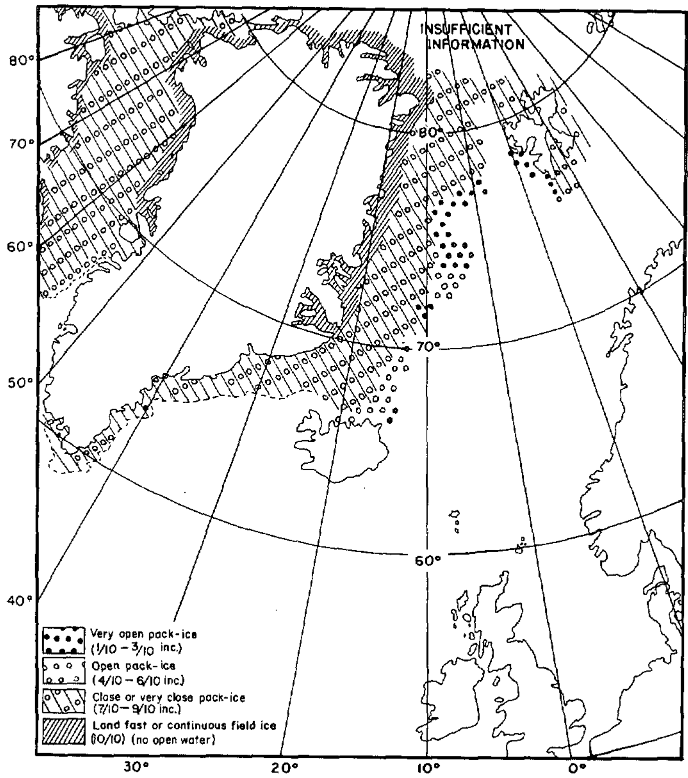


FIGURE 2.—Ice at the end of April 1965, from the Meteorological Office, Marine Division (1960–1969).

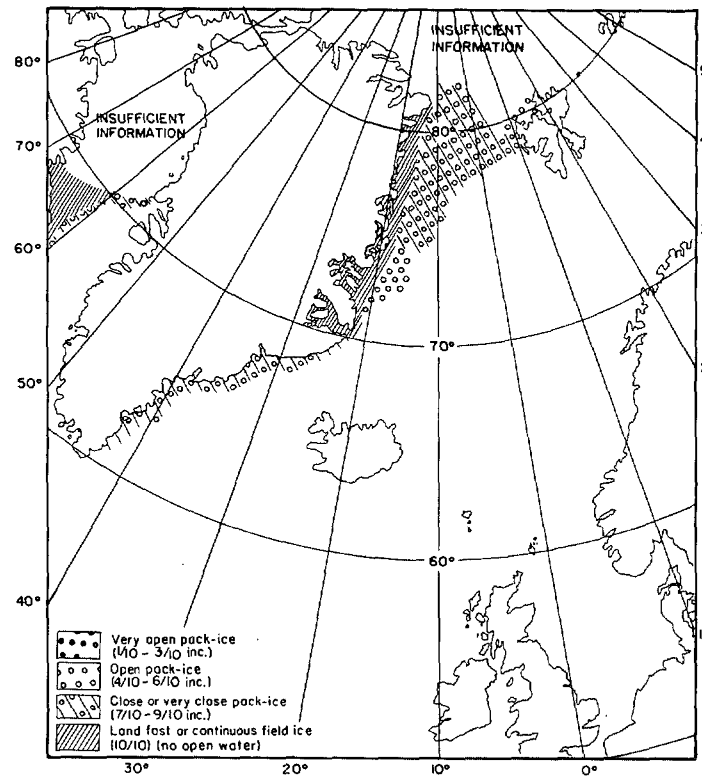


FIGURE 3.—Ice at the end of April 1960, from the Meteorological Office, Marine Division (1960–1969).

1952, 1954, 1956, 1957, 1959, 1960; Rasmussen 1949; Aleksejev et al. 1959*a*, 1959*b*, 1960, 1961; Jónsdóttir 1963; Istoshin and Shmarina 1963; Malmberg 1965; and Abrameiko 1965).

Thus the mean June sea temperatures (0–200 m) on a line crossing the East Iceland Polar Current from Langanaes on the northeast coast of Iceland to the island of Jan Mayen (table 5, section 6) in the northeast during 1957–1965 were relatively low in 1959, 1963, and 1965 but high in 1960 (fig. 4). Similarly, the August temperatures *and* salinities at Langanaes alone were low in 1949, 1963, and 1965 and high in 1947, 1954, 1957, and 1960 (table 3).

Altogether, on the basis of the results obtained from the different hydrographic sections and the sea-surface temperatures at Papey within the East Iceland Polar Current and also at Thorshavn in the Faeroes, we may identify 1944, 1949, 1952, 1959, 1963, and 1965 as years with relatively low temperatures and a strongly developed East Iceland Polar Current and the years 1946, 1947, 1954, 1956, 1957, and 1960 as years with relatively high sea temperatures and a weakly developed East Iceland Polar Current. The year 1960 is probably the warmest of the series, with the possible exception of 1947 for which no comparable data exist, while the inclusion of 1956 and 1957 in this category is somewhat doubtful (see below).

Earlier, we were able to indentify 1965, 1963, 1959, 1949, and probably also 1944 as severe ice years and 1960, 1957, 1956, 1954, 1947, and 1946 as light ice years.

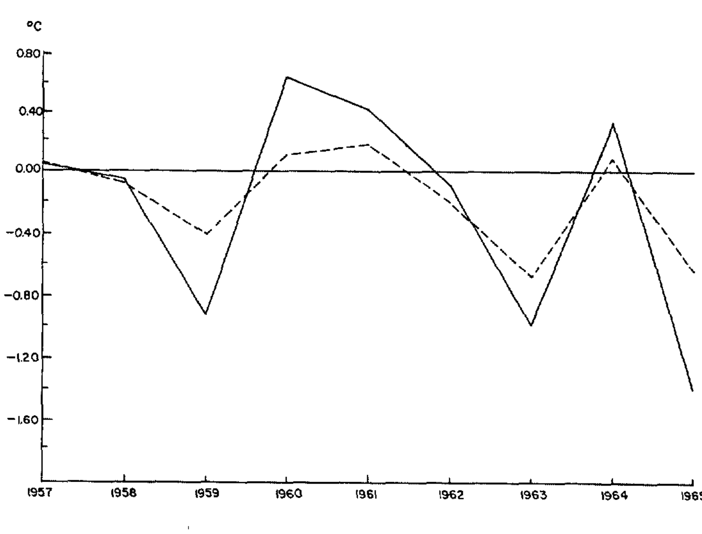


FIGURE 4.—June sea temperatures on a line from Langanaes (66°22′ N., 13°35′ W.) to Jan Mayen (71°01′ N., 8°28′ W.), after Aleksejev et al. (1961) and Abrameiko (1965).

Thus on the basis of ice conditions and to a lesser extent also sea temperatures, we obtain for the severe ice-low sea temperatures group the years 1965, 1963, 1959, 1952, 1949, and 1944 and for the light ice-high sea temperatures group the years 1960, 1957, 1956, 1954, 1947, and 1946, making 6 yr in each category.

TABLE 3.—*Deviations in temperature* (T) *and salinity* (S) *in August* at Langanaes (66°22′ N., 13°35′ W.), after Stefánsson and Gudmundsson (1969)*

Year	0 m		50 m		100 m		150 m		200 m		Mean 0–200 m	
	T, (°C)	S, (°/oo)	T, (°C)	S, (°/oo)	T, (°C)	S, (°/oo)	T, (°C)	S, (°/oo)	T, (°C)	S, (°/oo)	T, (°C)	S, (°/oo)
1947	1.60	−0.03	1.54	0.00	1.29	0.00	1.46	0.05	1.60	0.12	1.50	0.03
1949	−.49	−.41	−3.99	−.21	−2.38	−.15	−1.74	−.12	−1.84	−.14	−2.09	−.21
1954	.65	.00	1.09	.03	.97	.03	1.24	.04	1.34	.00	1.06	.02
1956	−1.75	.26	−.02	−.01	−.28	.02	.04	−.02	.39	−.02	−.32	.04
1957	.05	.20	.57	.15	.75	.03	.18	.02	.73	.03	.46	.09
1960	1.05	.08	.06	.16	.61	.07	.62	.09	.98	.10	.66	.10
1963	−1.84	−.05	.51	−.26	−1.23	−.10	−1.26	−.13	−.71	−.11	−.91	−.13
1965	−.95	−1.01*	−1.80	−.33*	−.44	−.18*	.00	-----------	.00	-----------	−.64	−.30
Average *	8.55	34.61	5.31	34.88	4.61	34.97	4.04	34.97	3.50	34.95	5.20	34.88
Std. dev.*	1.02	.22	1.38	.13	1.00	.07	.88	.08	.87	.08	-----------	-----------

* Based on the period 1934–1964 which also includes 1934, 1935, 1936, 1938, 1939, 1948, 1950, 1951, 1958, 1961, 1962, and 1964 (not shown here) of which only 1958 had a temperature deviation (Δ) at the surface in excess of ±0.50°C

4. ANALYSIS

In our examination of the different relationships, we propose to combine initially the extreme years, or years with a more southerly limit of the ice and relatively low sea temperatures (group I), and years with a more northerly ice limit and relatively high sea temperatures (group II).

If the results obtained from this composite analysis prove reasonably successful, we can then consider each year separately, bearing in mind additional factors that also play a part. To have begun with an analysis of individual years, we would have run the risk of seeing the relationship sought obscured by the other factors and more difficult to establish.

Accordingly, we have constructed two sets of composite charts or tables of each element and/or their differences, beginning with the sea-surface temperatures north of 50° N., followed by charts of the composite pressure distribution and zonal index over the North Atlantic and Europe-western Asia (60° W. to 90° E., north of 20° N.) and finally charts of temperature and precipitation for the April–September (contemporary with the ice and sea-surface temperature anomalies) and the four overlapping October–December, November–January, December–February, and January–March quarters to show the gradual eastward progression of the differences. To have attempted a greater degree of delineation by the use of individual months (October, November, etc.) would have implied a closer relationship than justified by the data at present.

SEA-SURFACE TEMPERATURE

Figure 5 gives the April–September composite sea-surface temperature differences (high less low) between the light and heavy ice years (L−H) in the areas A–N north of 50° N. on which are also entered the differences at OWS Bravo (Br), Charlie (Ch), Item (It), Juliett (Ju), and Mike (Mi) as well as Papey (P) on the east coast and Stykkisholmur (St) on the west coast of Iceland and Thorshavn (Th) in the Faeroes. This figure shows positive differences both in the area east of Iceland and also the other areas, except area E which is influenced by the mixed cold Labrador Current with warm Atlantic water. It is gratifying to note that for the most part the values derived from the OWS I and the three coastal stations (P, St, and Th) support the temperature data obtained by the International Council for the Exploration of the Sea based on the less frequent observations obtained by merchant vessels. (Areas A and E would seem to be too large for OWS Br and Ch to represent them adequately.)

The largest positive temperature differences, as one might expect, are found around Iceland, more particularly in area I (and at Papey) off the east coast, which is strongly influenced by the East Iceland Polar Current. The differences diminish southeastward in areas J and K and at Thorshavn. The fairly large positive differences to the south and west (areas G, F, H, C, and B) suggest that the Irminger Current also plays a role. For example, a stronger East Iceland Polar Current tends to be associated with a weaker Irminger Current during heavy ice years.

Figure 6, depicting the composite differences in sea-surface temperatures the following October–December, shows the trend for the positive difference (lower temperatures following heavy ice years than in light ice years) to have materially weakened, the difference in area I decreasing from 0.64°C in April–September to 0.36°C in October–December (at Papey from 1.1°C to 0.8°C). The differences have also become smaller in the adjacent areas G, H, J, and L. In the west (areas F, D, and B) and also in area K, the signs of the differences have actually reversed themselves. The values were similarly reduced in magnitude or have had their sign changed from positive to negative at OWS stations except Charlie, where the sign became positive.

In the following January–March, only Papey (and area E) registered a slight excess in temperature (0.1°C) in light over heavy ice years (fig. 7).

PRESSURE AND PRESSURE DIFFERENCES

For indices of the circulation that determines the southward movements of ice and polar water in the northeastern North Atlantic and the general trend of the

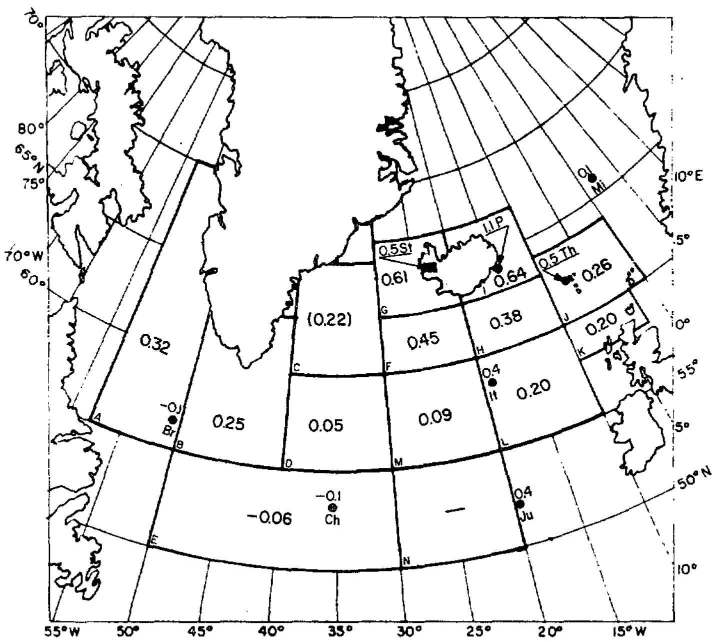


FIGURE 5.—April–September composite sea-surface temperature differences (light minus heavy ice years).

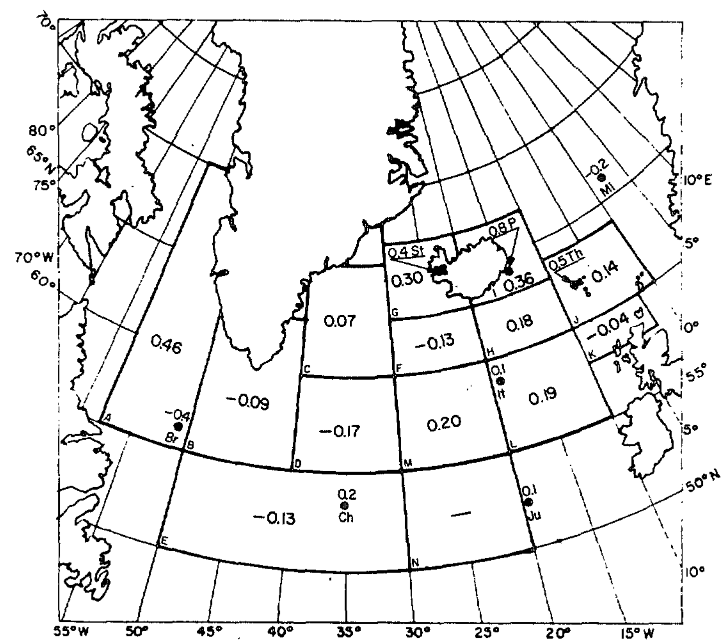


FIGURE 6.—October–December composite sea-surface temperature differences (light minus heavy ice years).

weather in the northeastern North Atlantic and also Europe, the Middle East, northern Pakistan, and India, we have constructed composite charts of the sea-level pressure distribution for both heavy and light ice years together with a chart showing the differences between them during April–September and the following October–December, November–January, December–February, and January–March quarters. It will be assumed that the October–December, etc., circulations reflect the April–September ice and sea temperature anomalies progressively later with increasing distance eastward or with the general movement of weather systems from west to east in the higher latitudes.

Beginning with the April–September period when the ice and the cold water generally associated with it attain the maximum southward penetration (in the first part of the period) and farthest northerly withdrawal (at the end of this period), we find the North Atlantic Low, as denoted by the 1011-mb isobar, reaching northeastward to northern Scandinavia or 20° E. (fig. 8A) and the Greenland High (1014 mb) extending to latitude 71° N. in heavy ice years, as compared with the same Low reaching longitude 5° W. or just east of Iceland (fig. 8B) and the Greenland High (1014 mb) extending to latitude 72° N. in light ice years. The lower pressures over the Barents Sea and higher pressures over Greenland in heavy ice years together denote a stronger west to east pressure fall (stronger northerly winds) and a stronger movement of ice and cold water southward. See also figure 9 showing negative sign pressure differences (higher pressures) over Greenland and positive sign differences (lower pressures) over the Barents Sea in heavy ice years.

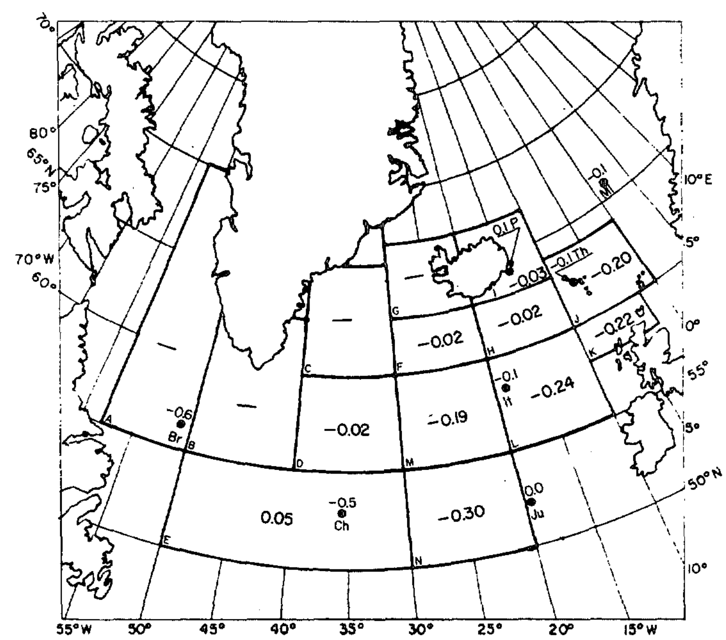
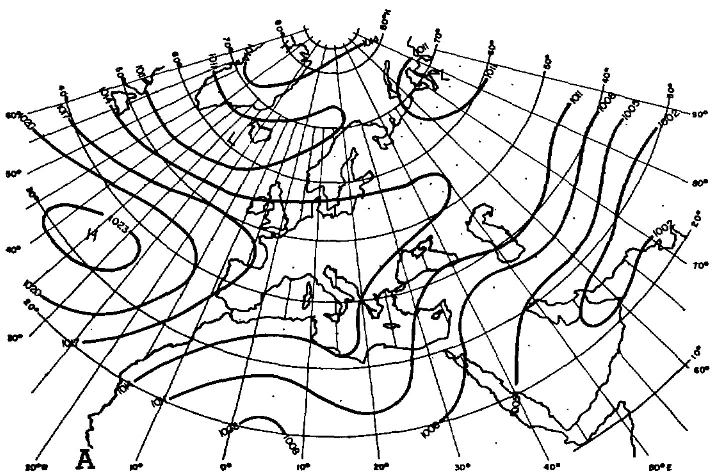


FIGURE 7.—January–March composite sea-surface temperature differences (light minus heavy ice years).

The differences in the pressure distribution between the two groups of years, as one might expect, are bigger in the October–December and the other succeeding cold quarters. Thus in October–December, the North Atlantic Low (1005-mb isobar) in light ice years reaches northeastward into the Barents Sea beyond 20° E., while the Greenland High (1011-mb isobar) extends southward to latitude 77° N. (fig. 10A) as compared with longitude 0° and latitude 72° N. for the North Atlantic Low and Greenland High,



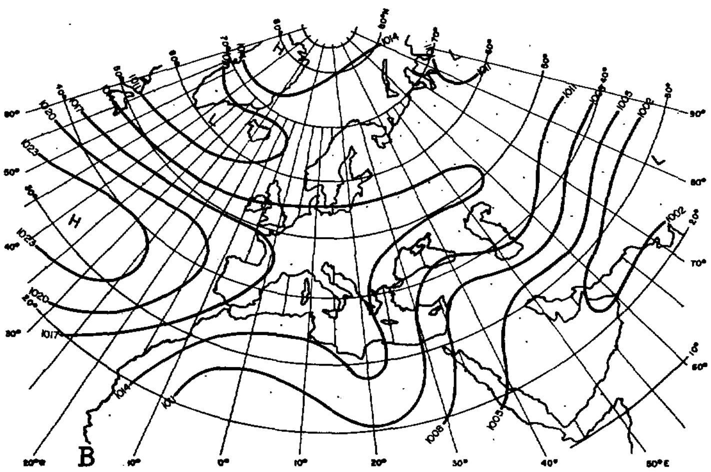


FIGURE 8.—April–September composite pressure in millibars for (A) heavy ice years and (B) light ice years.

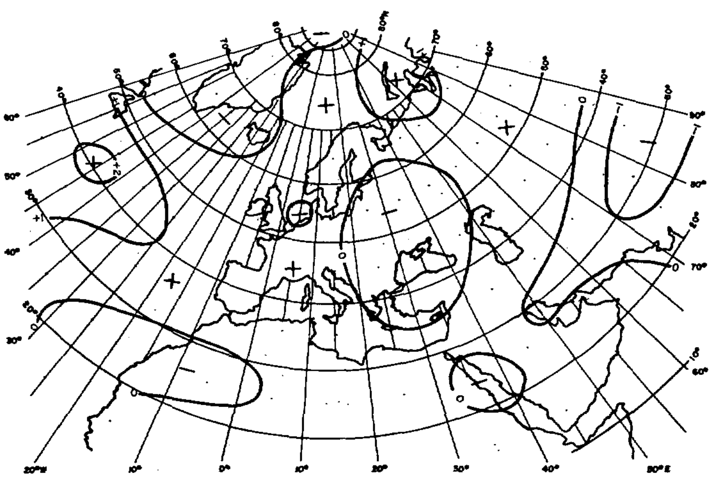


FIGURE 9.—April–September composite pressure differences in millibars (light minus heavy ice years).

respectively, in heavy ice years (fig. 10B). The change in pattern indicates a filling-in of the Low and its extension together with the Arctic High or its influence to lower latitudes as shown also by the area of positive sign pressure differences over much of Europe and the eastern North Atlantic and an area of negative sign pressure differences, over Greenland, the Greenland Sea and the Barents Sea, northern Europe, and northwestern Siberia (lower and higher pressures, respectively, in heavy than in light ice years, fig. 11).

The same process is repeated in the following November–January quarter with a pressure at the center of the North Atlantic Low of 999 mb in light ice years (fig. 12A) as compared with approximately 1005 mb in heavy ice years (fig. 12B) and a pressure of 999 mb in light ice years (fig. 14A) versus 1002 mb in heavy ice years (fig. 14B) in the December–February quarter.

Equally, along with the more southerly extension of the Arctic High, etc., in heavy ice years, the shallower Low is displaced farther southward and eastward in the November–January and December–February quarters, as can be seen from the areas of positive sign differences (lower pressure in heavy ice years). (See figs. 13 and 15.)

Also, starting with the December–February quarter, the pressure north of approximately 80° N. is lower in heavy than in light ice years as may be seen from the positive sign differences over northern Greenland (fig. 15). In the following January–March quarter (figs. 16A and 16B), the area of positive sign pressure differences takes in *all* of Greenland. In keeping with the reversal in the north, an area of negative sign pressure differences has developed over most of Europe, replacing the area of positive sign differences (fig. 17), together signifying the beginning of a reversal of the trend in the differences in the air movements between heavy and light ice years.

The above pattern of sea-level pressure differences is reflected also in the 700-mb height differences (not shown here) though not as evenly, presumably because the cold air outbreaks are sometimes too shallow to "show up" at this level (see section 6).

Thus on the basis of the circulation as reflected in the pressure patterns associated with heavy and light ice years, etc., we would expect lower temperatures and less precipitation in heavy ice years, as compared with light ice years, over the areas with higher pressures, as the Lows blocked by the higher pressures in the higher latitudes are forced to take a more southerly track. We would further expect the trend for lower temperatures and more precipitation in heavy as compared with light ice years to spread eastward and southward but end in the north and the west toward the end of the cold period, except as noted below.

ZONAL INDEX

For an additional analysis of the cold air outbreaks as a result of a greater accumulation of cold air in the higher latitudes in heavy as compared with light ice years, we have computed the zonal index (pressure difference 35° N. less 60° N.) over the North Atlantic and western Europe (60° W. to 10° E.) and similarly the index over eastern Europe and western Asia (20° E. to 90° E.) for the con-

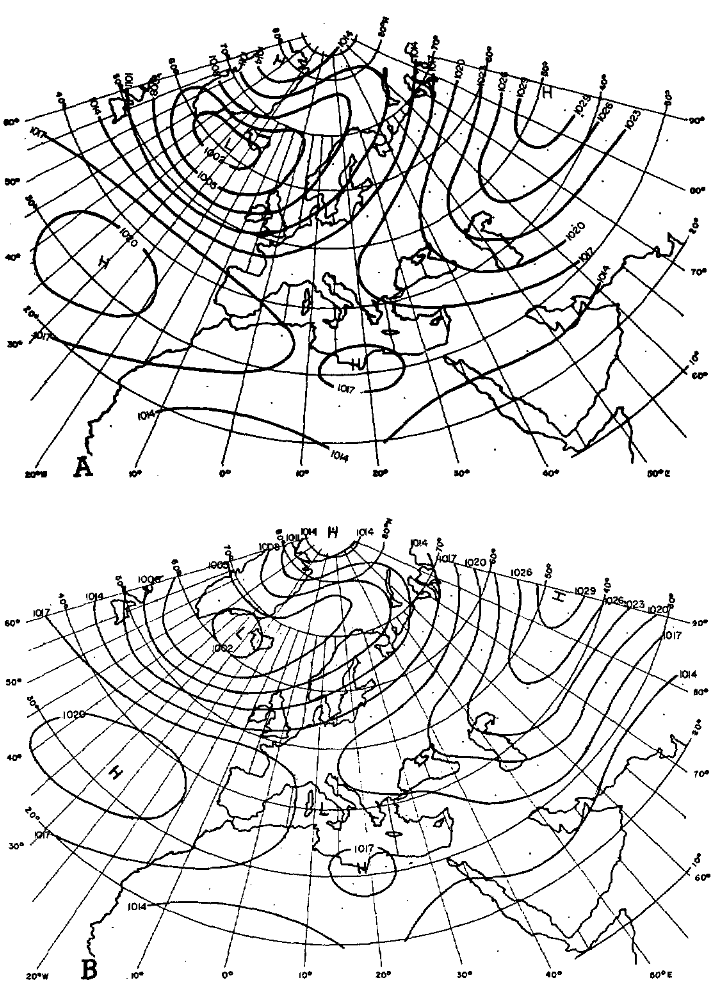


FIGURE 10.—October–December composite pressure in millibars for (A) heavy ice years and (B) light ice years.

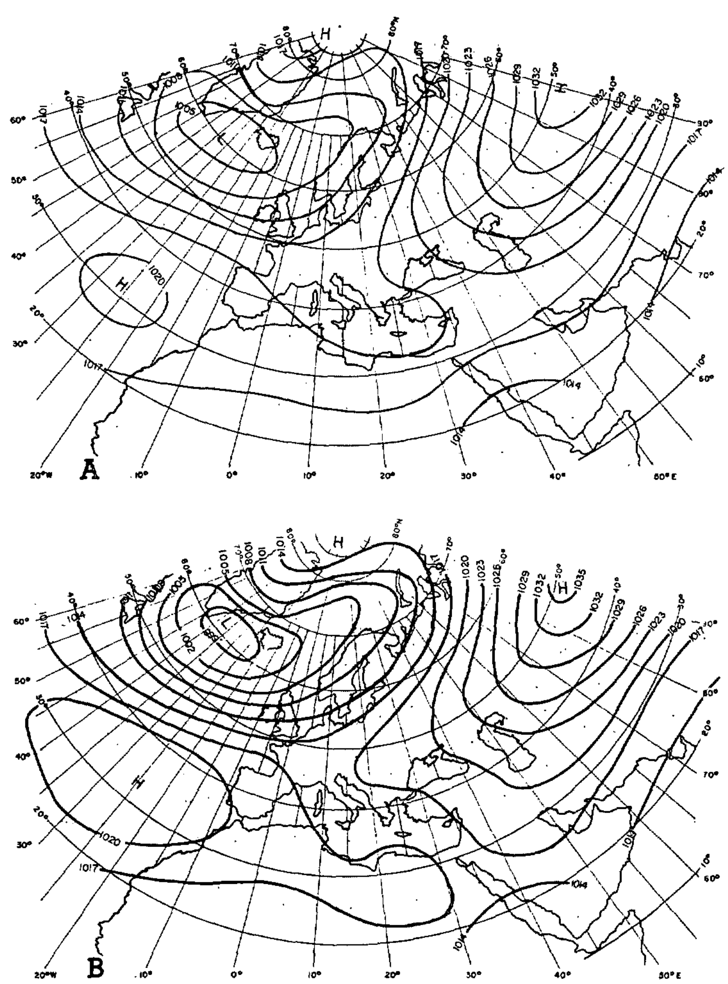


FIGURE 12.—November–January composite pressure in millibars for (A) heavy ice years and (B) light ice years.

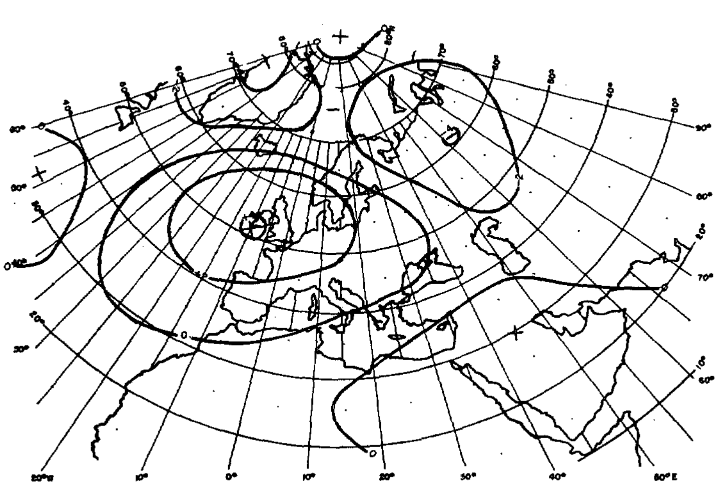


FIGURE 11.—October–December composite pressure differences in millibars (light minus heavy ice years).

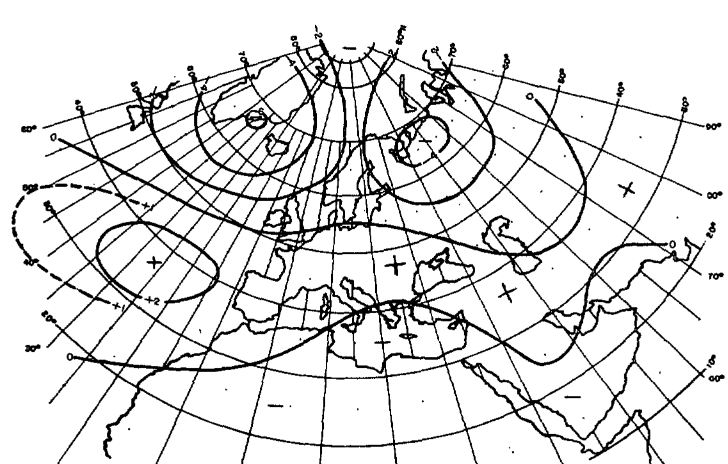


FIGURE 13.—November–January composite pressure differences in millibars (light minus heavy ice years).

temporary (April–September) and the following (October–December, etc.) quarters as shown in table 4.

The large April–September negative values of the index in both heavy and light ice years over the eastern Europe-western Asia sector (20° E.–90° E.) reflect the heated landmass or summer Low of the middle latitudes. Similarly, the positive values of the index in the North Atlantic, etc., reflect the high pressures over the relatively cool ocean in middle latitudes and the low pressure over the relatively warm ocean in the high latitudes in summer.

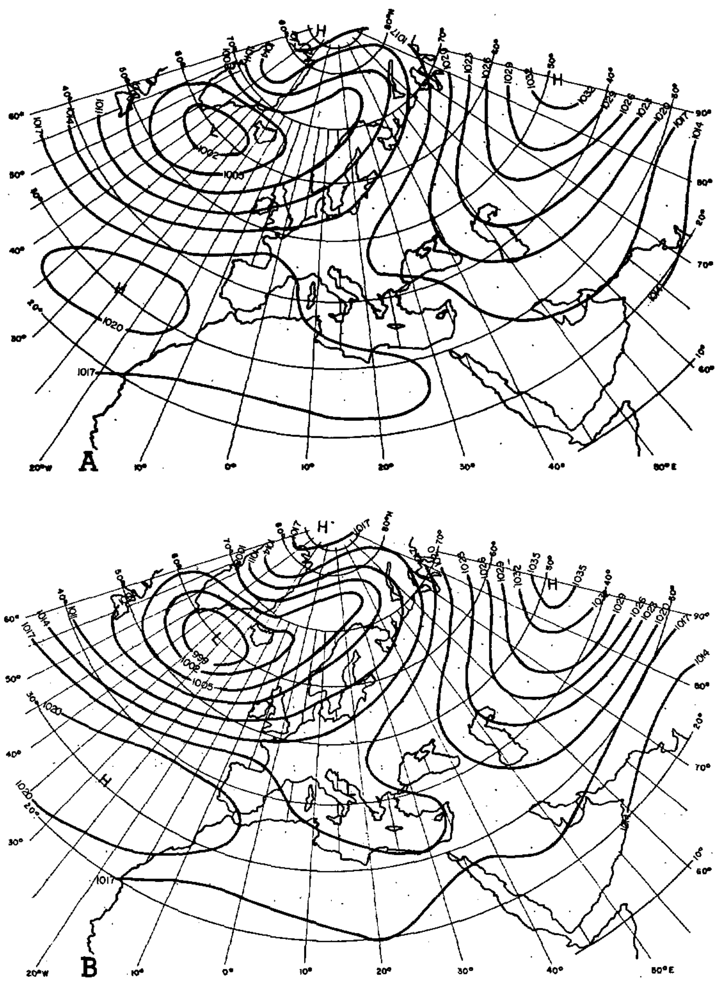


FIGURE 14.—December–February composite pressure in millibars for (A) heavy ice years and (B) light ice years.

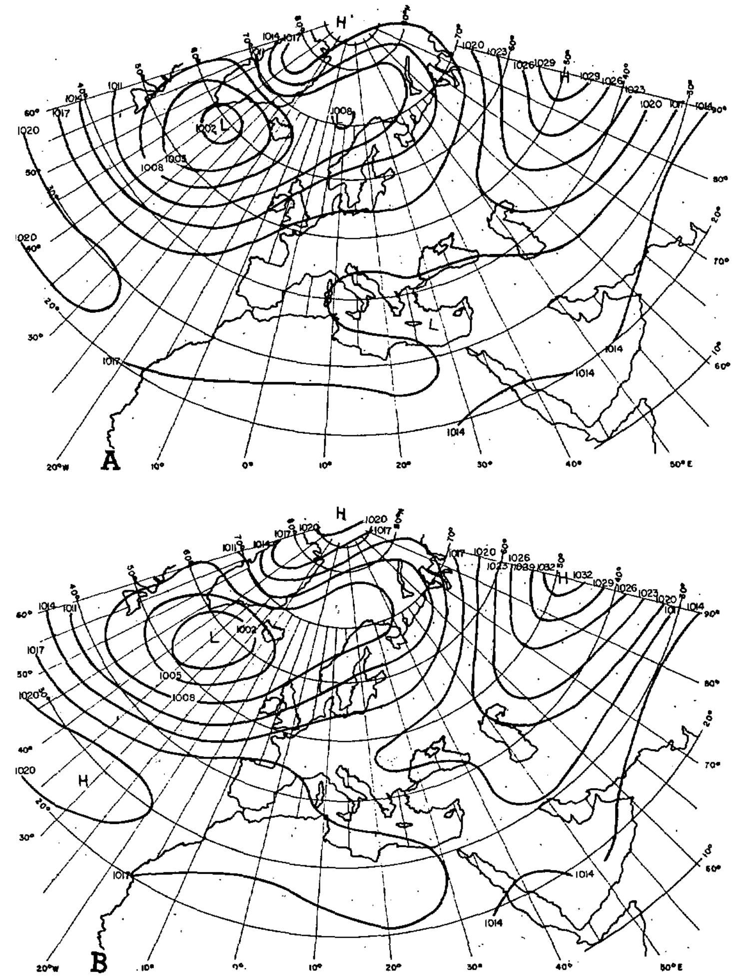


FIGURE 16.—January–March composite pressure in millibars for (A) heavy ice years and (B) light ice years.

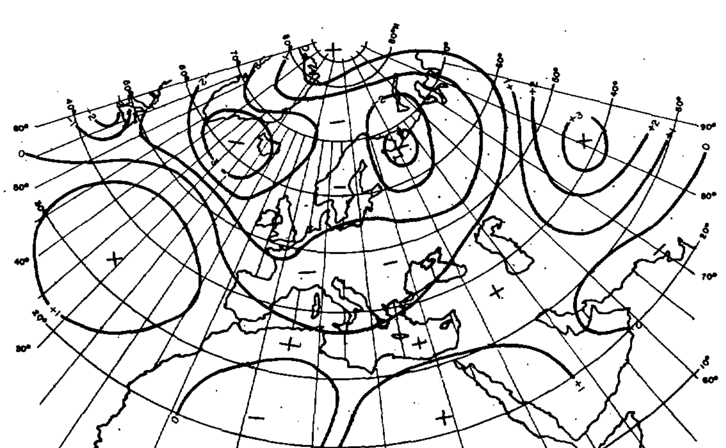


FIGURE 15.—December–February composite pressure differences in millibars (light minus heavy ice years).

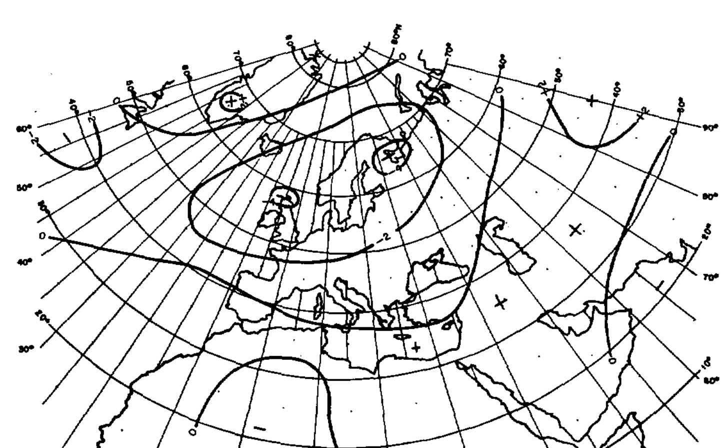


FIGURE 17.—January–March composite pressure differences in millibars (light minus heavy ice years).

Again, the small values of the index over the continental landmass in the cold period (October–March) reflect the accumulation of cold air to the north, the *negative* values of the index reflecting the *greater* accumulation of cold air in heavy than light ice years.

The differences in the zonal index over the North Atlantic between heavy and light ice years, after showing an increase from October–December to November–January, show a decrease from 3.4 mb (November–January) to 1.6 mb (January–March), suggesting an end

TABLE 4.—*Composite sea-level zonal index (pressure 35° N. less 60° N.) in the North Atlantic (60° W.–10° E.) and Europe-western Asia (20° E.–90° E.) for groups I and II years and their differences* (L–H), *all in millibars*

	Apr.–Sept.	Oct.–Dec.	Nov.–Jan.	Dec.–Feb.	Jan.–Mar.
			North Atlantic		
L	9.7	14.2	16.7	16.6	12.2
H	8.6	14.6	13.3	13.4	10.6
Diff.	1.1	−.4	3.4	3.2	1.6
			Europe-western Asia		
L	−4.3	0.7	1.0	0.8	0.9
H	−4.1	−1.0	−1.5	−1.6	−2.0
Diff.	−.2	1.7	2.5	2.4	2.9

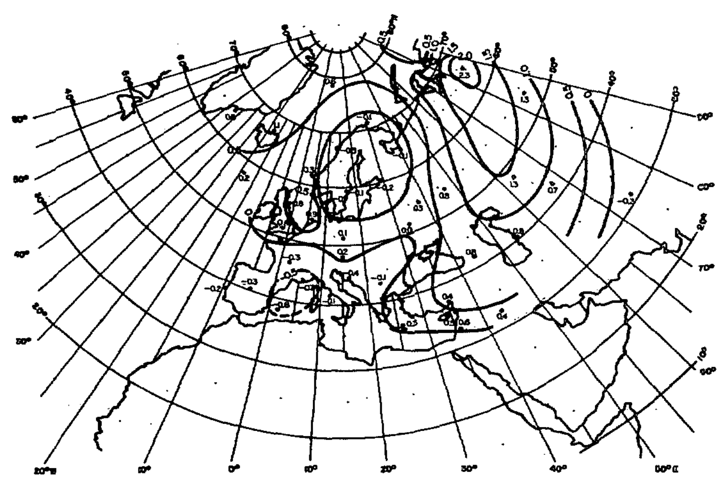


FIGURE 19.—October–December composite temperature differences (light minus heavy ice years).

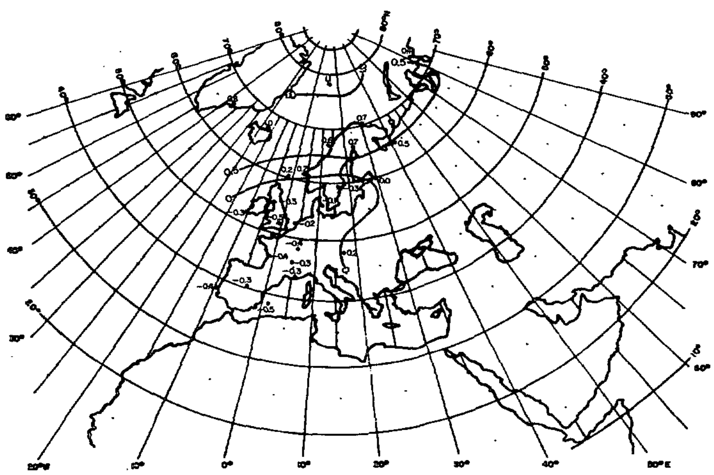


FIGURE 18.—April–September composite temperature differences (light minus heavy ice years).

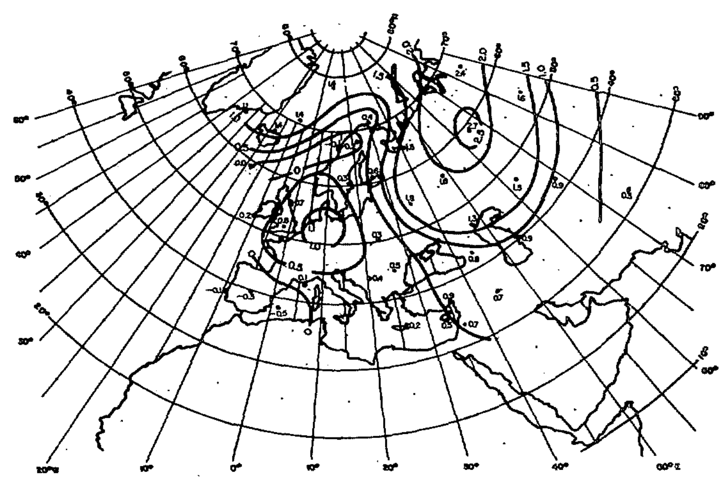


FIGURE 20.—November–January composite temperature differences (light minus heavy ice years).

of the differences in the cold air outbreaks between heavy and light ice years over the North Atlantic and western Europe in the December–February and the January–March quarters. Similarly, the increase in the differences in the index over eastern Europe-western Asia (20° E. to 90° E.) from 1.7 mb in the October–December quarter to 2.9 mb in the January–March quarter suggests more frequent cold air outbreaks in heavy than in light ice years over that area in the latter part of the cold period. This suggests that the April–September sea ice and sea temperature anomalies would show a closer correlation on the whole with the eastern North Atlantic and northwestern Europe air temperatures in the October–December than the January–March quarters and show a closer correlation with the eastern Europe and western Asia air temperatures in the following January–March than in the October–December quarters. The air temperatures of the higher latitudes except in the west (Greenland and Iceland) would be expected to show a correlation during the entire cold period.

TEMPERATURE

Figures 18 through 22, depicting the differences in temperature between the light and heavy ice years (light minus heavy), show lower temperatures (positive sign differences) in the April–September period (fig. 21) along the west coast of Greenland (Angmagsalik, 0.6°C), Iceland (Akureyri, 1.0°C), Jan Mayen (0.6°C), and Spitzbergen (1.1°C) as well as over northern Scandinavia (Vardo, 0.7°C, Bodo, 0.6°C, and Haparanda, 0.7°C), the northernmost USSR (Archangelsk, 0.5°C, and Turukhansk, 0.5°C), and at OWS station I (59°00′ N., 20°00′ N.), (0.5°C), reflecting the influence of a better developed Arctic High and stronger northerly winds in heavy ice years as compared with light ice years. To the south in western Europe, we find a weak field of higher temperatures (negative sign differences) in heavy than in light ice years. (See also table 5, section 6.)

The temperature differences in the following October–December, November–January, etc., quarters reflect a spread of the colder air in heavy ice years to lower latitudes with the strongest outbreaks over the USSR—yet also with evidence, beginning with the November–January

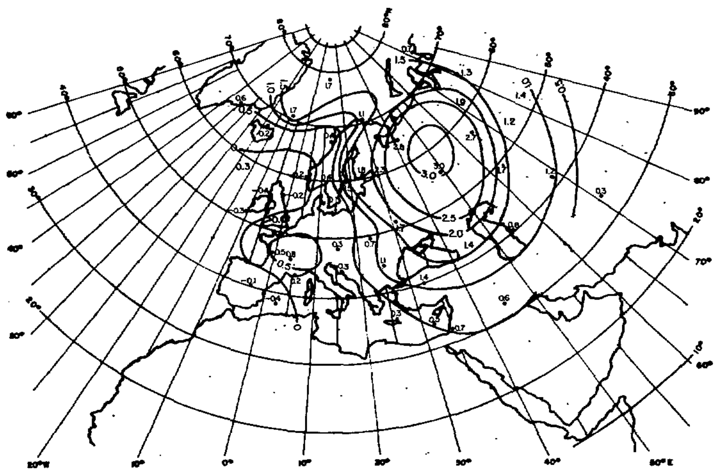


FIGURE 21.—December–February composite temperature differences (light minus heavy ice years).

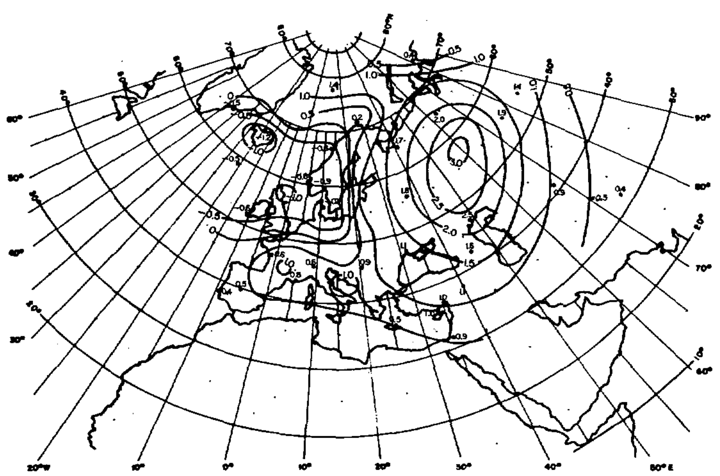


FIGURE 22.—January–March composite temperature differences (light minus heavy ice years).

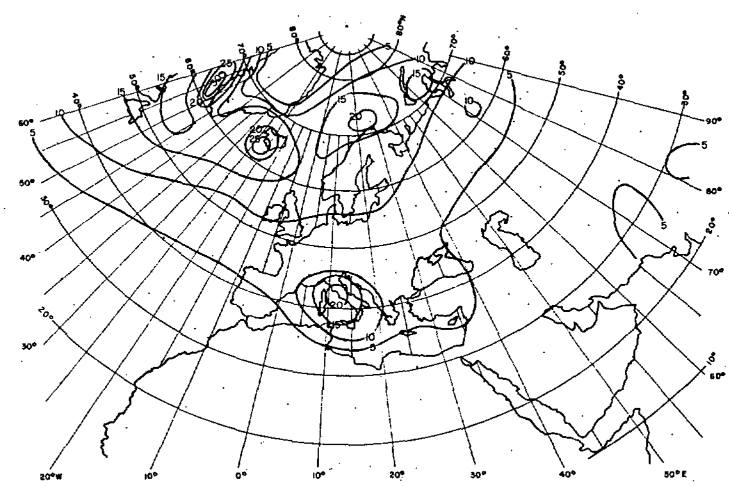


FIGURE 23.—Number of days (×10) during October–December 1899–1938 with a low-pressure center at 1230 GMT in each 5° square (Klein 1957).

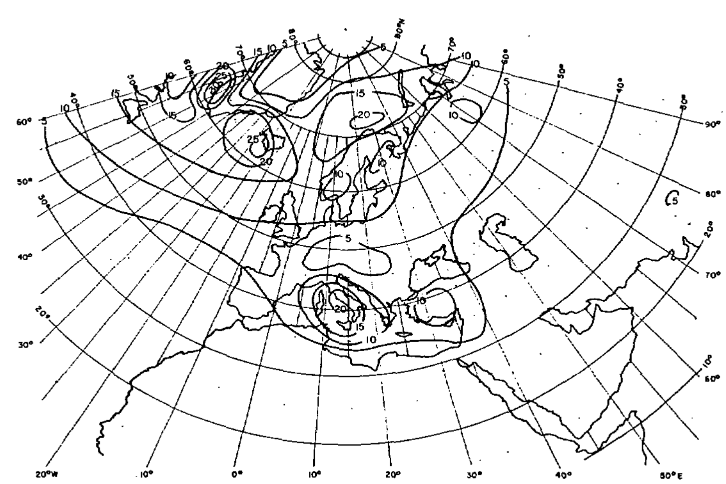


FIGURE 24.—Number of days (×10) during November–January 1899–1938 with a low-pressure center at 1230 GMT in each 5° square (Klein 1957).

quarter, of a tongue of negative sign differences (higher temperatures in heavy ice years) moving in toward Norway which in the following January–March quarter spreads to Iceland, Ireland, the United Kingdom, the Low Countries, and southern Norway, in effect reversing the October–December trend in these areas.

PRECIPITATION

By way of introducing our consideration of the relationship with the precipitation, we present the average (1899–1938) frequency of Lows recorded at 1230 GMT over the area during the October–December, November–January, December–February, and January–March quarters (figs. 23–26) together with the favored trajectories of the primary and secondary tracks of Lows for the individual months during the October–March cold season (fig. 27).

Figures 23–26 show high concentrations of Lows (in excess of 250) in the Davis Strait, the vicinity of Iceland, and the Barents Sea with another area of high frequencies (in excess of 200) in the central Mediterranean in each of the four quarters. Beginning with the November–January quarter, an area of relatively high storm frequency (>100) appears also over the eastern Mediterranean, and finally another area (>150) appears over northern Pakistan and India in the following January–March quarter. The later development of more frequent storminess in northern Pakistan and India would be consistent with the "distance" the North Atlantic storms crossing into the Mediterranean by way of the Bay of Biscay and also those developing as secondaries or independently in the Mediterranean (Mull and Desai 1947, Sutcliffe 1960, and Levi 1963) would have to travel. This suggests that for northern Pakistan and India the principal season affected by the April–September anomalies in the North Atlantic would be the following November–March or December–March months (fig. 27).

On the whole, the relationship with the precipitation would be expected to be more complex than with the

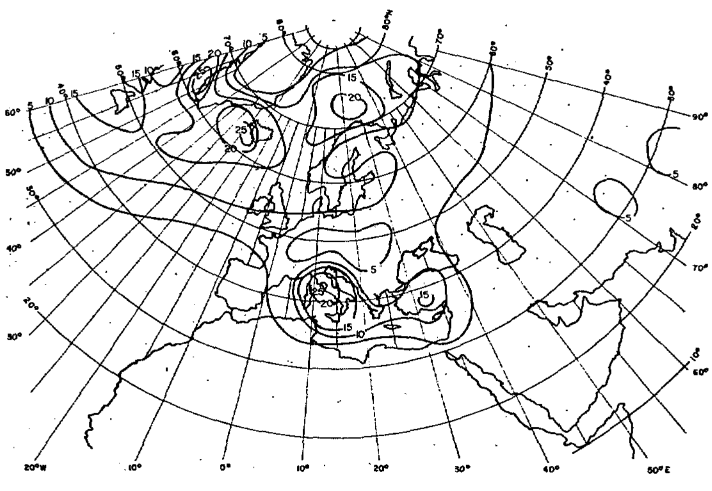


FIGURE 25.—Number of days (×10) during December–February 1899–1938 with a low-pressure center at 1230 GMT in each 5° square (Klein 1957).

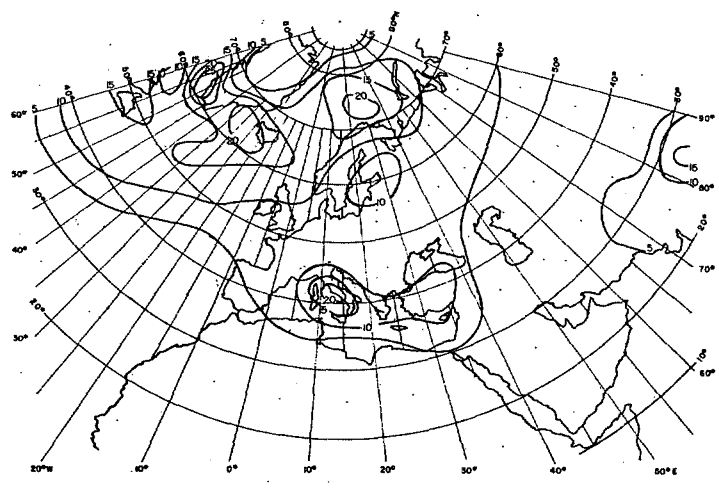


FIGURE 26.—Number of days (×10) during January–March 1899–1938 with a low-pressure center at 1230 GMT in each 5° square (Klein 1957).

temperature. We showed how a southward spread of the Arctic High (higher pressures in heavy than in light ice years) would lead to lower temperatures over the regions with a negative sign pressure difference in the north and also to the south, as the cold air spills over in the middle latitudes (figs. 9, 11, 13, 15, and 17). The precipitation on the other hand would increase in the region with lower pressures (positive sign differences) in the south toward which the storm track has shifted, but decrease in the north over the region with higher pressure (negative sign differences) from which the track has shifted away. Thus, the precipitation during October–December would be expected to be less in heavy than light ice years over Iceland, Jan Mayen, Spitzbergen (see below), Norway (west of the Scandinavian mountain range), northern Russia, and northwestern Siberia as the storm track shifts southward away from this region. East of the Scandinavian mountain range or over most of Sweden, Finland, and the Baltic Sea region as well as the United Kingdom Ireland, Denmark, Holland, France, western Germany, and northern Italy to which the low pressure field has shifted and also in the eastern Mediterranean and the southern USSR where storm activity has increased, the precipitation would be expected to be heavier (Schell 1947). The precipitation would also be expected to be heavier in heavy ice years in the east and southeast toward the end of the cold period, while in the west and northwest the trend for differences in the precipitation between heavy and light ice years would be expected to be lessened or disappear altogether. The above appears to be the case as seen from figures 28–32 giving the ratios (percent) of the differences in precipitation between the composite six heavy and the composite six light ice years (heavy minus light) to the average precipitation of the 6 light ice years for 14 regions representing a total of 75 stations in the northeastern North Atlantic, Europe, western Siberia, the Middle East, northern Pakistan, and India. The plus sign values in the figures show heavier precipitation (greater storm activity), and the minus values show lighter precipitation (decreased storm activity) in heavy than in light ice years.

The notable exception to the above in the north is the heavier precipitation in heavy ice years in Spitzbergen, although the temperatures there are lower. Figures 11, 13, and 15 show that this region lies *between* two areas with minus sign pressure differences (higher pressure in heavy ice years) or in a trough, and we may suppose that it is under the additional influence of convergence whereby ascending air has its moisture released.

As an added expression of the relationship between the spring–summer sea ice and sea temperature anomaly in the northeastern North Atlantic and the following cold season precipitation, their composite October–December values for 17 stations in western Europe (United Kingdom, Ireland, Denmark, etc.) were reduced to their long-term averages. This gave a deviation of 15.9 percent per station per heavy ice year and −1.7 percent per station per light ice year. The small average negative deviation for light ice years appears to have resulted from the relatively abundant precipitation associated with the strong westerlies in 1960 when the storm track retreated *far* to the north and the Azores High moved up northward (not shown here). The strong moist westerlies coming from the ocean produced considerable orographic precipitation, enough to compensate for much of the loss due to greatly diminished storminess.

5. ROLE OF SEA ICE AND SEA TEMPERATURE ANOMALIES

In developing our thesis that the ice and sea temperature anomalies during April–September influence the subsequent weather locally and progressively later to the eastward and southward, we are aware that these anomalies originate to a large extent in the atmospheric circulation, essentially in stronger or weaker northerly winds not only contemporaneously (April–September) but also from the winds the January–March before.

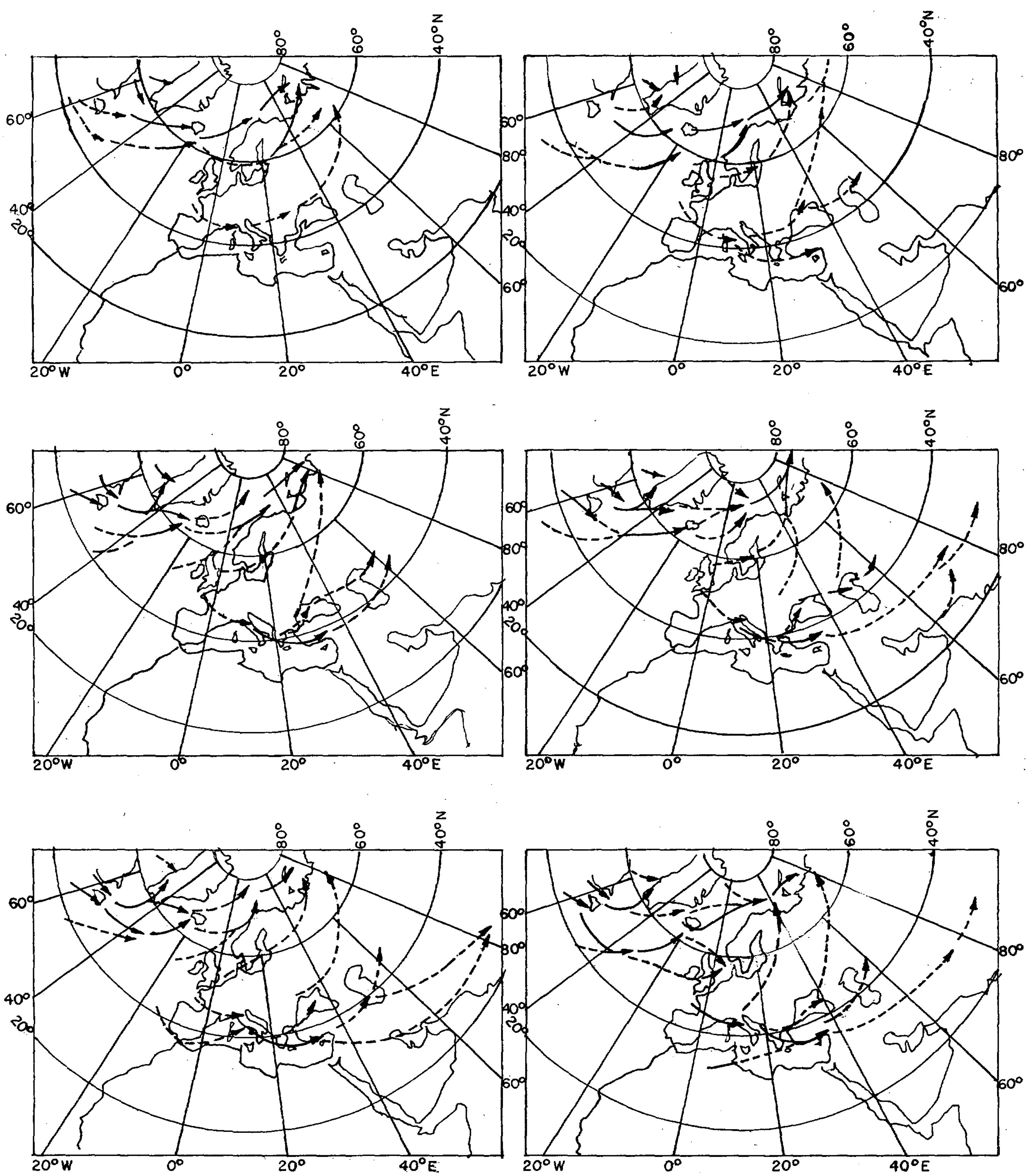


FIGURE 27.—Primary (solid arrow) and secondary (broken arrow) October through March storm tracks. Arrows begin in approximate regions of local maximum cyclogenesis, and arrowheads end where cyclone frequency is a local maximum (Klein 1957).

To see how this process operates, we have constructed for this quarter composite pressure and 700-mb height charts for both groups of years (figs. 33 and 34) and also of the differences (figs. 35 and 36) between them (light less heavy) both at sea level and the 700-mb height level, respectively, as well as a chart (fig. 37) of the differences in the sea-surface temperature (light less heavy).

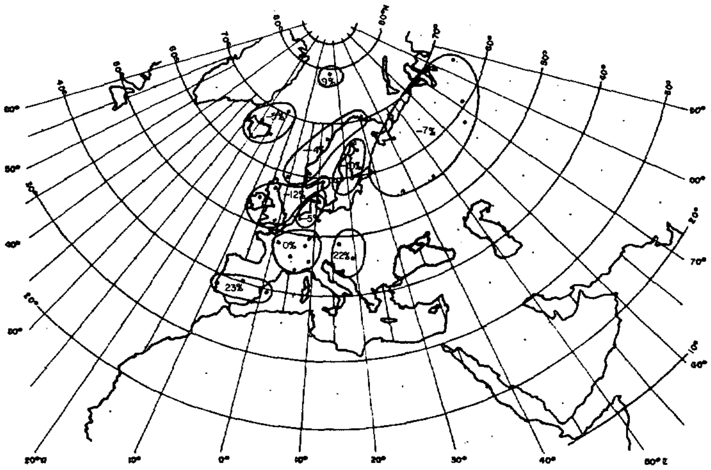


FIGURE 28.—April–September composite precipitation differences (heavy minus light ice years); plus-sign areas, more precipitation; minus-sign areas, less precipitation.

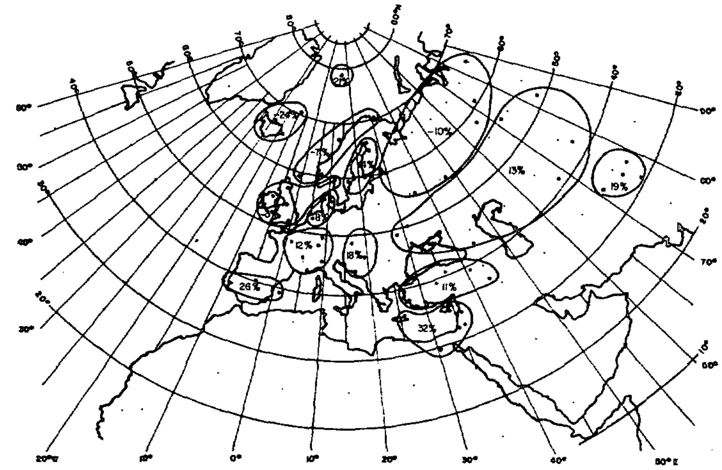


FIGURE 30.—November–January composite precipitation differences (heavy minus light ice years); plus-sign areas, more precipitation; minus-sign areas, less precipitation.

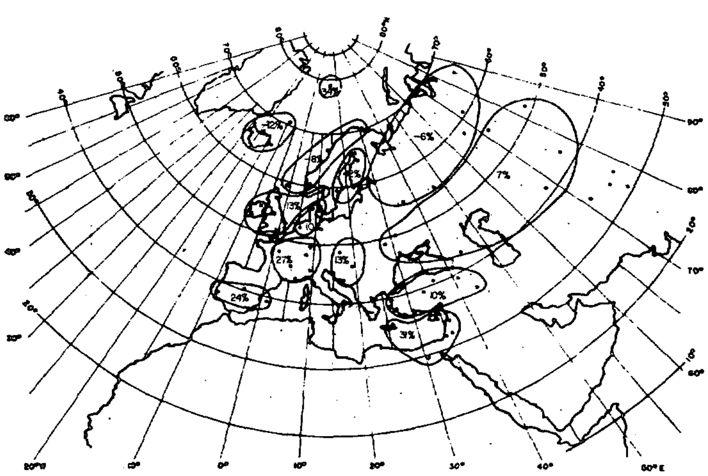


FIGURE 29.—October–December composite precipitation differences (heavy minus light ice years).

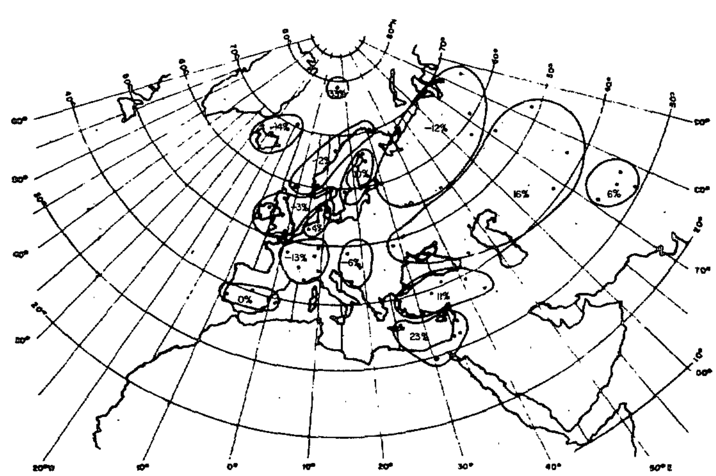


FIGURE 31.—December–February composite precipitation differences (heavy minus light ice years).

Figures 33 and 34 show that in years with relatively light ice and higher sea temperature the winds in the north (pressure fall at latitude 70° N. between western Greenland, 20° W., and northern Scandinavia, 50° E.), are markedly weaker (10.8−12.1=−1.3 mb), actually from the south, than in years with relatively heavy ice and lower sea temperatures (8.1−6.3=1.8 mb).

The intensity of the northerly air flow in heavy ice years can further be judged from the small but well-developed Low north of Scandinavia (fig. 33) and from the differences in pressure at sea level and at the 700-mb height level between the heavy and light ice years (light minus heavy), showing larger plus values (lower pressures in heavy ice years) over the Barents Sea as compared with Greenland (fig. 35). The fact that the Low over the Barents Sea extends to the 700-mb level (fig. 36) and undeniably some distance above it suggests that the strong northerly winds are likely to persist for a considerably time and that the circulation during January–March, before the ice season, could be the determining factor in the weather in the months ahead.

At the same time, the positive sign sea-surface temperature differences (light minus heavy ice years) during April–September (fig. 5) were higher in most areas than in the January–March before (fig. 37), as for example: 0.45°C versus 0.18°C (area F), 0.64°C versus 0.38°C (area I), and 0.26°C versus 0.18°C (area J). This suggests a reinforcing role for the April–September sea anomalies of the trend initiated the January–March before.

Yet the fact that the sea-surface temperature differences in the following January–March quarter are mostly negative (fig. 7) rather than positive as in the preceding quarters suggests that the weather to the eastward could be influenced slightly by these anomalies. This would seem to suggest that the primary role in determining the weather, for time intervals the length of a season, is prob-

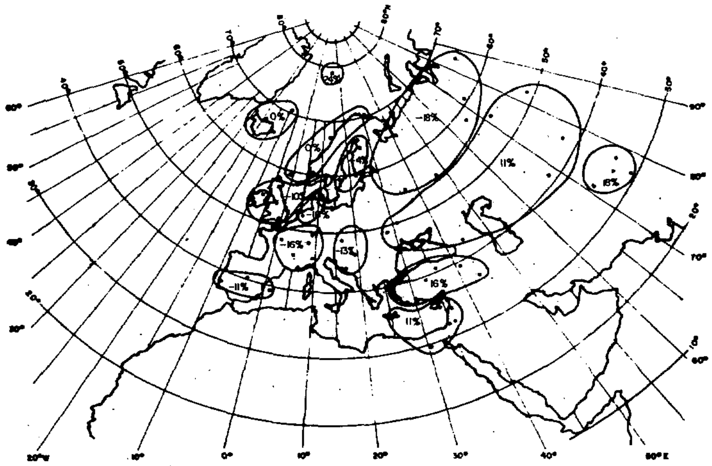


FIGURE 32.—January–March composite precipitation differences (heavy minus light ice years); plus-sign areas, more precipitation; minus-sign areas, less precipitation.

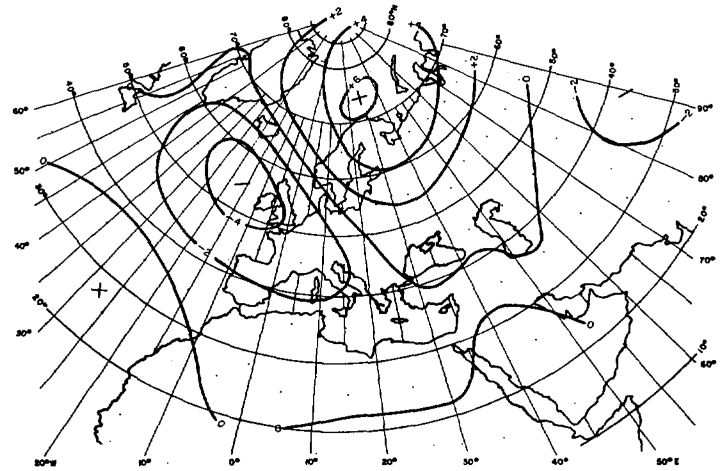


FIGURE 35.—January–March composite pressure differences in millibars (light minus heavy ice years).

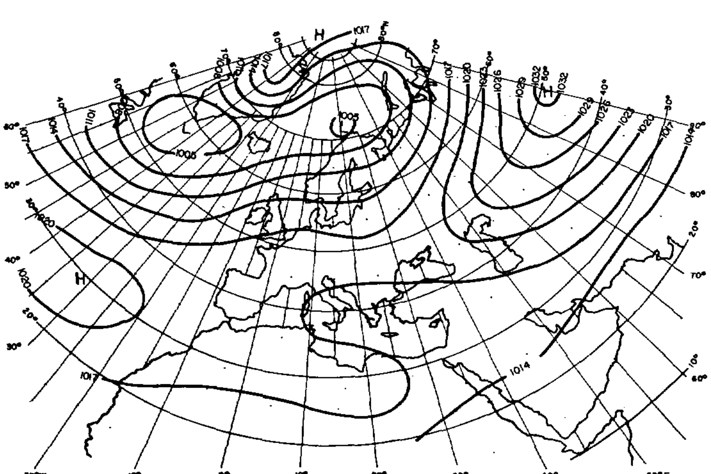


FIGURE 33.—January–March composite pressure in millibars (heavy ice years).

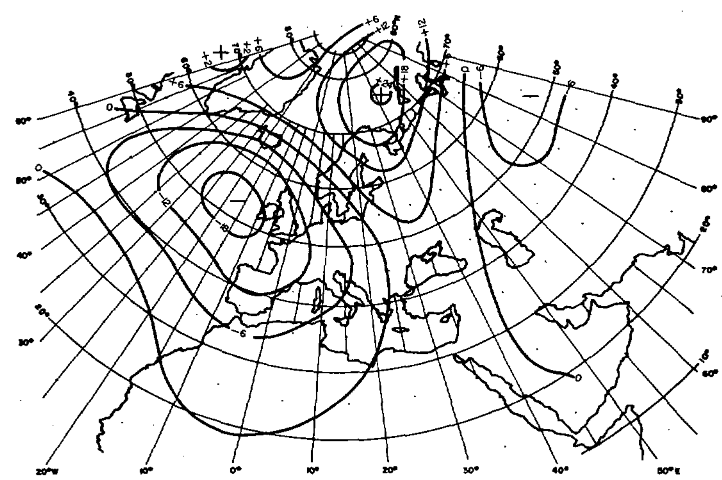


FIGURE 36.—January–March composite 700-mb height differences in meters (light minus heavy ice years).

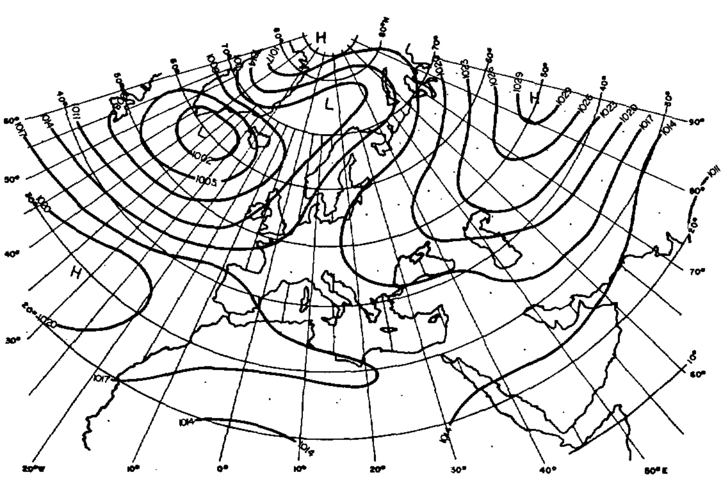


FIGURE 34.—January–March composite pressure in millibars (light ice years).

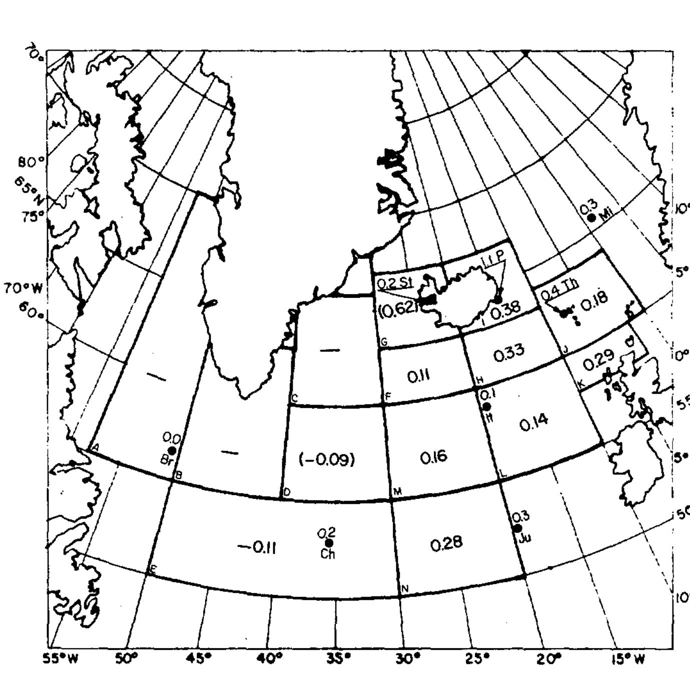


FIGURE 37.—January–March composite sea-surface temperature differences (light minus heavy ice years).

ably the atmospheric rather than oceanic circulation and that for the ocean's dominant role in weather anomalies requires a longer time interval.

6. SIGNIFICANCE OF THE RESULTS FOR FORESHADOWING, AND FURTHER REMARKS

The results obtained allow us to outline an orderly sequence of weather for some months ahead from an analysis of the persistent characteristics of the ocean and the atmosphere locally, and, because of the general movement of weather systems from west to east in the middle and high latitudes, progressively later also to the eastward.

As a by-product, the relationship between the ice and sea anomalies in the northeastern North Atlantic and the following weather in Europe and western Asia suggests a basis for foreshadowing the seasonal temperature and precipitation for years with large deviations in the ice and sea temperatures from the average. But before we can achieve this, we need to delineate the relationship also for individual years.

The precise role of the atmosphere and of the ocean in this sequence would not be easy to evaluate. An intense Low, for example over the Barents Sea, owes its development in part to relatively high sea temperatures. At the same time, the development of relatively high sea temperatures would be due in part to strong southerly or southwesterly winds bringing warm water into the Barents Sea. The ability to fix the precise role of each in this sequence need not be a condition for determining the broad features of the atmospheric and oceanic circulation and potentially for foreshadowing the cold season weather locally and to the eastward. For example, a relatively warm Barents Sea on the one hand and a very cold ice-covered Greenland on the other can lead to stronger northerly winds and to a greater southward transport of cold water and ice in the northeastern North Atlantic in the spring–summer.

By taking advantage of the fact that the oceans and the atmosphere are inherently slow to change over longer periods, while often exhibiting sharp short-period or daily changes, we can show with the aid of physical synoptic analysis substantial control of the weather locally; and *because of the movements of air and water along broadly established paths from areas with local control upwind to areas with little or no local control (eastward) in the middle and higher latitudes* (Schell 1956*b*), we can show the control of the weather of these areas as well.

The fact that the ice and sea temperature anomalies during April–September are in a large measure determined by the winds in January–March suggests that a perceptive analysis of the circulation in the northeastern North Atlantic and adjacent areas, before the active ice season, could provide a basis for foreshadowing in April the following cold season temperature and precipitation of Europe and western Asia. The foreshadowing could be confirmed early in October from the observations made during April–September.

TABLE 5.—*List of stations*

Austria	Wien
Czechosolvakia	Prague, Kosice
Cyprus	Nicosia
Denmark	Copenhagen, Vestervig
France	Lyon, Marseille, Nantes
Finland	Helsinki
Germany	Frankfurt a/M, Hohenpeissenberg, Trier
Greece	Athens, Heraklion
Hungary	Budapest
Iceland	Akureyri, Stykkisholmur, Teigarhorn
India (north of 30° N.)	Simla, Leh
Iraq (northern)	Mosul
Ireland	Markree Castle, Valentia
Israel	Beersheba, Har Kenaan, Lod
Italy (upper)	Milano
Jan Mayen	
Jordan	Amman
Netherlands	De Bilt
Norway	Bergen, Bodo, Oslo, Vardo
Pakistan (north of 30° N.)	Lahore, Peshawar
Poland	Gdansk, Przemysl, Wroclaw
Portugal	Lisbon
Romania	Bucharest, Sibiu
Spain	Madrid, Palma
Spitzbergen	Isfjord Radio
Sweden	Haparanda, Karesuando, Upsalla
Switzerland	Zurich, Santis
Turkey	Ankara, Antalya, Erzurum, Istanbul, Izmir, Rize, Samsun
Union of Soviet Socialist Republics (Europe)	Arkhangelsk, Astrakhan, Kazan, Kiev, Leningrad, Lvov, Moscow, Odessa, Tbilisi
Union of Soviet Socialist Republics (Asia)	Alma Ata, Barnaul, Krasnovodsk, Omsk, Surgut, Tashkent, Tobolsk, Turgai, Turukhansk
United Arab Republic (northern)	Helwan
United Kingdom	Aberdeen/Dyce, Eskdalemuir, Kew, Lerwick

The term "foreshadowing" as used here denotes a prediction of the average temperature and total rainfall for a longer period such as a season. It differs from a forecast, which aims at a day-by-day prediction of the weather ahead, in that it takes cognizance of a certain instability in the atmosphere (which can speed up or delay the movement of individual weather systems) but which over a longer period must conform to the overall demand by the basic anomaly in the atmosphere and in the ocean, leading to a trend that becomes apparent when the daily weather has been averaged.

The apparent lesser agreement obtained from the comparison based on the 700-mb height differences (not shown here) was, we suspected, due to the frequent shallowness of the cold airmasses in Europe in winter. This is confirmed by the temperature differences at the high elevation station Santis (2496 m) with the neighboring Zurich (569 m). The difference in temperature between heavy and light ice years (light minus heavy) for the December–February quarter at Zurich was 0.8°C as compared with −0.2°C at Santis, showing the effect of subsidence of the cold air at the latter. (See also table 5.)

The lack of agreement with the rainfall from stations in lower Italy (not shown here) would be due to the intense *local* storms in the central Mediterranean (figs. 23–26) whose rainfall would overshadow the influence of the North Atlantic storms crossing into the Mediterranean. Similarly, the lack of agreement with the rainfall of Iran and southeastern Iraq would be due to the Persian Gulf disturbances, overshadowing the influence of storms moving over this region from the west, and to the extensive modification of the precipitation by the high mountain barriers in Iran.

Our selection of heavy and light ice and relatively low and high sea temperature years was, inevitably, to a certain extent arbitrary. Yet the years chosen agreed for the most part with independent determinations made by others. For example, our choice of 1946 as a warm and 1952 as a cold year (within the period 1946–1953) was the same as that by Shiskov (1962). On the other hand, we might have selected 1961 over 1957 as a warm year and regarded 1956 as an average rather than a warm year.

On the whole, our experiment, based on a composite representation of the different elements for the study of the persistent characteristics of the circulation and their effect on the subsequent weather locally and to the eastward, was reasonably successful; and we may now move on to delineating the relationships for each year separately by taking advantage of the greater body of the sea ice, sea temperature, cloud, wind, and other weather observations made available by satellites, airplanes, ocean weather ships, and other means of observation.

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